The Effects of Marine Winds from Scatterometer Data on Weather Analysis and Forecasting

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ABSTRACT

Satellite scatterometer observations of the ocean surface wind speed and direction improve the depiction of storms at sea. Over the ocean, scatterometer surface winds are deduced from multiple measurements of reflected radar power made from several directions. In the nominal situation, the scattering mechanism is Bragg scattering from centimeter-scale waves, which are in equilibrium with the local wind. These data are especially valuable where observations are otherwise sparse—mostly in the Southern Hemisphere extratropics and Tropics, but also on occasion in the North Atlantic and North Pacific. The history of scatterometer winds research and its application to weather analysis and forecasting is reviewed here. Two types of data impact studies have been conducted to evaluate the effect of satellite data, including satellite scatterometer data, for NWP. These are *simulation* experiments (or observing system simulation experiments or OSSEs) designed primarily to assess the potential impact of planned satellite observing systems, and *real data* impact experiments (or observing system experiments or OSEs) to evaluate the actual impact of available space-based data. Both types of experiments have been applied to the series of satellite scatterometers carried on the Seasat, *European Remote Sensing-1* and *-2,* and the *Advanced Earth Observing System-1* satellites, and the NASA Quick Scatterometer. Several trends are evident: The amount of scatterometer data has been increasing. The ability of data assimilation systems and marine forecasters to use the data has improved substantially. The ability of simulation experiments to predict the utility of new sensors has also improved significantly.

1. Introduction

One of the important applications of satellite surface wind observations is to increase the accuracy of weather analyses and forecasts. Satellite surface wind data can improve numerical weather prediction (NWP) model forecasts in two ways. (Acronyms are listed in appendix A.) First, these data contribute to improved analyses of the surface wind field, and, through the data assimilation process, of the atmospheric mass and motion fields in the free atmosphere above the surface. Second, comparisons between the satellite-observed surface wind data and short-term (6 h) forecasts can provide information to improve model formulations of the planetary boundary layer, as well as other aspects of model physics. The first satellite to measure surface wind vectors over the oceans was Seasat in 1978. (Table 1 contains a list of satellite scatterometers.) The Seasat-A Satellite Scatterometer (SASS) measured radar backscatter from centimeter-scale capillary waves, from which surface wind speed and direction could be deduced. Seasat also carried a scanning multichannel microwave radiometer (SMMR). Geophysical parameters retrieved from SMMR include wind speed. Since then and especially since the launch of the Special Sensor Microwave/Imager (SSM/I) in 1987 aboard the Defense Meteorological Satellite Program *F8* spacecraft, and the active microwave instrument (AMI) in 1991 aboard the *European*

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TABLE 1. Satellite scatterometers.

Spacecraft/instrument	Dates	Type
Seasat/SASS	1978	Ku band
ERS-1/AMI	1991–96	C band
ERS-2/AMI	1995–present	C band
ADEOS-1/NSCAT	1996–97	Ku band
QuikSCAT/SeaWinds	1999–present	Ku band
ADEOS-2/SeaWinds	2001 launch	Ku band
METOP/ASCAT	2003 launch	C band

Remote Sensing-1 (*ERS-1*) spacecraft, satellite-borne microwave sensors have provided extensive observations of ocean surface wind.

The initial effect of satellite surface wind data on weather analysis and forecasting was very small (e.g., Baker et al. 1984, and other references in section 5), but extensive research has been conducted since the early days of Seasat to improve the data accuracy and the utilization of these data in atmospheric models. Current satellite surface wind data are used to improve the detection of intense storms over the ocean as well as to improve the overall representation of the wind field in NWP models. As a result, these data are contributing to improved warnings for ships at sea and to improved global weather forecasts. In this paper we focus on scatterometer data, but in an earlier paper (Atlas et al. 1996) we described how the SSM/I wind speed data have been used to create a multiyear global surface wind velocity dataset.

Two types of experiments related to the effectiveness of atmospheric observations in data assimilation are described in this paper. Both types of experiments are termed impact experiments because these experiments are designed to demonstrate significant or major effects, (usually) of a type of data on the quality of weather analyses and forecasts. Hence the term impact as used here denotes the effect of a particular type of data. The two types of experiments are called observing system simulation experiments (OSSEs) and observing system experiments (OSEs), respectively. In an OSE a Control data assimilation is followed by one or more experimental assimilations in which data of a particular type are either withheld or added to the Control. Analyses and forecasts generated from both the Control and experimental assimilations are then verified and compared in order to determine the impact of each data type being evaluated. Experiments performed in this manner provide a quantitative assessment of the value of a selected type of data to a specific data assimilation system (DAS). OSEs cannot be conducted for proposed new instruments. Instead OSSEs are used. In an OSSE the true state of the atmosphere or "nature" is simulated by a long forecast of an NWP model. The process of making observations of the atmosphere is also simulated for both conventional and experimental observing systems. The simulated observations are then used in various different experimental configurations, as in an OSE.

Prior to the launch of Seasat, OSSEs indicated a large positive impact. However, the subsequent OSEs showed a generally negligible impact of these data, when used only at the surface. Vertical extension of surface wind observations increases the impact, but simple extension that does not account for the synoptic situation gives negative as well as positive effects. More consistent positive impact results from the use of stability-dependent vertical correlation functions (Bloom and Atlas 1990, 1991).

Recent experiments with the Goddard Earth Observing System (GEOS) DAS indicate that the impact of National Aeronautics and Space Administration (NASA) Scatterometer (NSCAT) data was larger than for other satellite surface wind datasets studied. The results of OSEs with the GEOS DAS showed improvements of more than 500 km in the forecast location of cyclones over the oceans. The resulting improvement to numerical weather forecasts was equivalent to about a 24-h extension in useful forecast skill in the Southern Hemisphere extratropics. This impact was found to be approximately twice as large as the impact of SSM/I or *ERS-1* scatterometer wind data, in the same data assimilation system. These results confirmed predictions made in earlier OSSEs conducted at the NASA Data Assimilation Office (DAO).

Because specific impact results are expected to vary with the DAS used, these OSEs have been conducted using a variety of DASs. At the DAO these have included the GEOS-1 DAS (Schubert et al. 1993), the GEOS-2 DAS (Atlas et al. 1999), and an earlier version of the National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center) global DAS (Parrish et al. 1997). In general, impacts tend to be smaller when using the most advanced DAS. However, in the experiments reported here, more dramatic improvements were obtained with GEOS-2 than with GEOS-1. Current operational systems, for example, at the European Centre for Medium-Range Weather Forecasts (ECMWF) or NCEP or the new higher-resolution GEOS-3 DAS, are more advanced, and impacts on such systems are expected to be somewhat smaller. Preliminary NSCAT experiments with the ECMWF system to date show only small or negative impacts (see section 8). However, ECMWF and NCEP have shown positive impacts with the *ERS-1,2* scatterometer data (see section 7).

The plan of this paper is as follows: section 2 describes the data coverage available from satellite scatterometers. A brief review of the scatterometer measurement of surface wind is then given in section 3. The impact study methodology and special handling of scatterometer data that have been developed are described in section 4. Section 5 describes some early experiments conducted using SASS data. Results of OSSEs for *ERS-1* and NSCAT are described and compared in section 6. Then sections 7 and 8 present OSEs for *ERS-1* and NSCAT, respectively. Preliminary results using NASA's conically scanning scatterometer SeaWinds on the NASA Quick Scatterometer (QuikScat) are presented in section 9. The experience of marine forecasters in using scatterometer data is described in section 10. Finally section 11 contains concluding remarks and future plans for SeaWinds.

2. Data coverage

Prior to the launch of satellites capable of determining surface wind from space, observations of surface wind velocity were provided primarily by ships and buoys. Such conventional observations are important components of the global observing system, but are limited in coverage and accuracy. For example, reports of surface wind by ships cover only very limited regions of the world's oceans, occur at irregular intervals of time and space, tend to avoid the worst (and therefore most interesting) weather, and are at times of poor accuracy. Buoys are of higher accuracy and provide a continuous time history, but have even sparser coverage. As a result, analyses based solely on these in situ observations can misrepresent the surface wind over large regions and are generally not adequate for weather forecasting.

Satellites offer an effective way to fill data voids as well as to provide higher-resolution and more accurate data than are available routinely. The first space-based scatterometer was a SKYLAB experiment (Jun 1973–Feb 1974). Based on this experience Seasat carried the SASS instrument in 1978 (Grantham et al. 1977). This mission failed after only approximately 100 days. However, the SASS data were of sufficient quality and interest (Stewart 1988; Katsaros and Brown 1991) that plans for a follow-on mission were quickly formulated (O'Brien et al. 1982). Unfortunately the SASS follow-on was not launched until 1996 as NSCAT aboard the *Advanced Earth Observing System-1* (*ADEOS-1;* Naderi et al. 1991), and *ADEOS-1* failed after only nine months. [Chelton et al. (2000) provide a very useful appendix describing NSCAT.] Data gathered by NSCAT were excellent. The follow-on to NSCAT, called SeaWinds (Shirtliffe 1999), was launched in June 1999 aboard QuickSCAT, with another copy to be launched in November 2001 aboard ADEOS-2. The scatterometers mentioned so far are all NASA instruments and all operate in the Ku band (~14 GHz). During the interim between SASS and NSCAT, the European Space Agency (ESA) successfully designed, built, and launched the *ERS-1* satellite in July 1991 and then the *ERS-2* satellite in April 1995. Each carries an AMI, which operates as a C-band (~5 GHz) scatterometer for most of each orbit (Francis et al. 1991). Both Ku-band and C-band instruments have successfully met or exceeded their design specifications (Table 2).

A single scatterometer of the ERS AMI design provides coverage over 90% of the ocean within 96 h. A single scatterometer of the NSCAT design provides coverage over 90% of the ocean within 48 h. The newer SeaWinds design provides over 90% coverage within 24 h. Typical 6-h coverage for each of these instruments is shown in Fig. 1.

As the spatial coverage and number of scatterometers has increased the number of scatterometer surface wind observations has increased, and is expected to continue to increase with SeaWinds on QuikSCAT and ADEOS-2. In Fig. 2, the approximate total number of observations is plotted versus time, and extrapolated into the future based on announced launch dates. This figure does not include the possible extended *ERS-2* mission or the anticipated follow-on to *ERS-2,* called ASCAT (for advanced scatterometer) on the planned Meteorological Operational (METOP) satellite.

TABLE 2. Ocean surface vector wind requirements from the S^3 report (O'Brien et al. 1982), which may be considered to be the preliminary design document for NSCAT; the *ERS-1* design (Francis et al. 1991); the NSCAT design (Naderi et al. 1991); and the SeaWinds design (Shirtliffe 1999). Resolution is the nominal spacing of the retrieved wind vectors. Precision for that of the standard products.

Authority		**S^3 report**	***ERS-1***	**NSCAT**	**SeaWinds**
Coverage:	resolution	50 km	25 km	50 km	25 km
	refresh	—	—	90% / 48 h	90% / 24 h
Speed:	accuracy	2 m s^{-1} or 10%	2 m s^{-1} or 10%	2 m s^{-1} or 10%	2 m s^{-1} or 10%
	precision	—	0.1 m s^{-1}	0.01 m s^{-1}	0.01 m s^{-1}
	range	4–24 m s^{-1}	4–24 m s^{-1}	2–30 m s^{-1}	3–30 m s^{-1}
Direction:	accuracy	±20°	±20°	±20°	±20°
	precision	—	±1°	±0.01°	±0.01°

3. Measurement of surface winds from satellite scatterometers

Scatterometers illuminate the earth's surface with a series of pulses of polarized microwave radiation. In the interval between pulses the power of the backscattered signal is measured. These measurements are averaged to enhance the signal. The measurement process adds noise during the detection and amplification stages in the radar. Separate measurements of the noise alone are made between series of pulses. The measured noise is removed from the measured signal plus noise to obtain the reflected power. Consequently, for low wind speeds, when the true reflected power is very small, the estimated reflected power may be negative (Pierson 1989). The radar equation is then used to convert the power measured to the normalized radar cross section (NRCS) or backscatter. The word scatterometer was coined by R. K. Moore in the mid-1960s (W. J. Persion, 2001; personal communication). The designs of individual instruments are described by Grantham et al. (1977) for SASS, Francis et al. (1991) for ERS AMI, Naderi et al. (1991) for NSCAT, and Shirtliffe (1999) for QuikSCAT. Each scatterometer design has different characteristics that are relevant to the use of the data. A schematic of the observing patterns of these instruments is given in Fig. 3. The scatterometers launched have all had similar orbit characteristics—sun synchronous, near-polar orbits, at roughly 800-km altitude, with a period of approximately 100 min. SASS and NSCAT had antennas on both sides of the spacecraft, affording two simultaneous swaths (each 500 km wide for SASS and 600 km wide for NSCAT) separated by a nadir gap (450 km wide for SASS and 350 km wide for NSCAT). SASS had two antennas on each side, while NSCAT had three antennas on each side. SASS operated in a variety of modes with different polarizations. The NSCAT antennas were vertically polarized for fore and aft, and vertically and horizontally polarized for the midantenna. The *ERS-1* scatterometer has three vertically polarized antennas only on the right side of the spacecraft. Due to the geometry of these fan beam instruments, the backscatter values at a single location are observed within a time span of approximately 70–200 s, increasing with incidence angle. SeaWinds has a radically new design, using a 1-m rotating dish antenna to illuminate two spots on the earth's surface, which sweep out two circular patterns (Spencer et al. 2000). With this design there is no nadir gap, and in the region of overlap away from nadir there are essentially four independent measurements. For SeaWinds the backscatter values at a single location are observed within a time span of up to 290 s, increasing as the location approaches nadir.

Over the ocean, scatterometer surface winds are deduced from multiple backscatter measurements made from several directions. In the nominal situation, the scattering mechanism is Bragg scattering from centimeter-scale waves, which are in equilibrium with the local wind. Theoretical models have made much progress in recent years, but most scatterometer winds

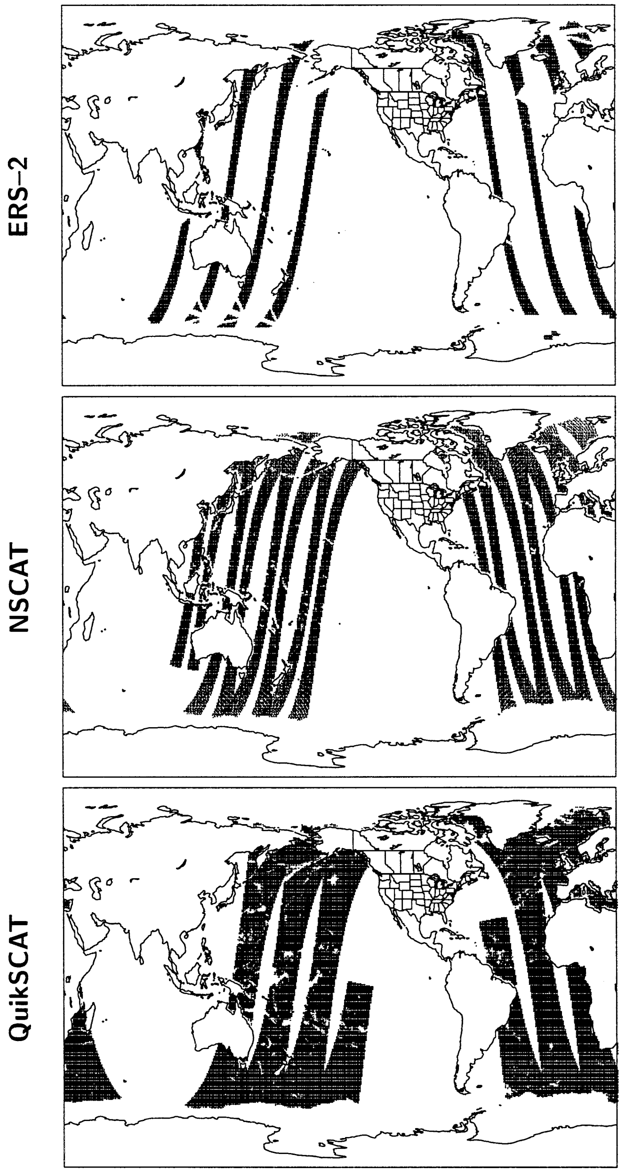

FIG. 1. Scatterometer data coverage in 6 h for (top) *ERS-1,* (middle) NSCAT, and (bottom) Sea-Winds.

are derived with the aid of empirical relationships, called model functions, which relate the NRCS to the geophysical parameters, and which are derived from collocated observations (Jones et al. 1977; Stoffelen and Anderson 1997b; Wentz and Smith 1999). The surface roughness is more a direct measure of the surface stress than of the near-surface wind (Pierson et al. 1986). Therefore all collocated wind measurements are first corrected for stability and elevation effects to a standard height and neutral conditions. (The standard height is now usually 10 m, but was 19.5 m for some earlier model functions.) As a result, winds retrieved from scatterometers are the effective wind speed and

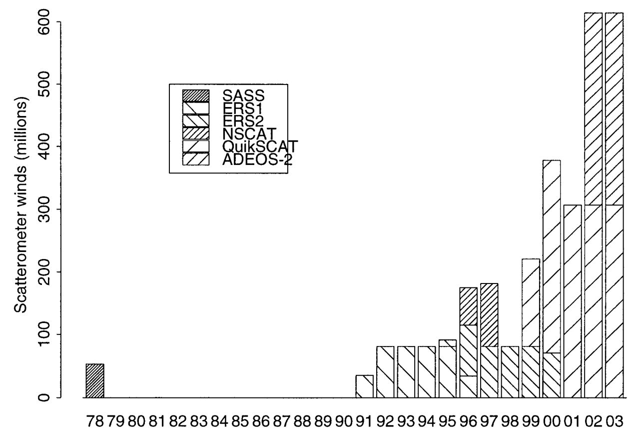

FIG. 2. Millions of scatterometer wind observations per year. The contributions of the different instruments are indicated. These are estimates based on the following assumptions: There are no data drops from the date of the first wind until the mission terminated or, in the case of *ERS-1,* was put in standby status. Five full years of scatterometer winds will be obtained for current and planned instruments. SeaWinds wind observations will begin Jan 2002. Winds are retrieved at a resolution of 25 km. The numbers of cross-track wind vector cells are 48, 19, 48, and 72 for SASS, *ERS-1,2,* NSCAT, and SeaWinds. Due to land and ice, 50% of all wind vector cells have retrieved winds. Possible effects of rain on data coverage are ignored.

direction at the standard height for a neutrally stratified atmosphere. In current model functions, the NRCS depends nonlinearly on wind speed and direction. To first order NRCS increases linearly with the logarithm of the wind speed and varies biharmonically with χ, the wind direction relative to the antenna pointing direction. The biharmonic or $\cos(2\chi)$ dependence arises because, in the absence of fetch effects, the roughness of the small-scale waves looks the same if

	SASS	ERS-1/2	NSCAT	SeaWinds
FREQUENCY	14.6 GHz	5.3 GHz	13.995 GHz	13.6 GHz
AZIMUTHS				
POLARIZATION	V-H, V-H	V ONLY	V, V-H, V	V-OUTER/H-INNER
BEAM RESOLUTION	FIXED DOPPLER	RANGE GATE	VARIABLE DOPPLER	PENCIL-BEAM
SCIENCE MODES	MANY	SAR, WIND	WIND ONLY	WIND/HI-RES
RESOLUTION	50/100 km	25/50 km	25/50 km	25 km/6x25km
SWATH		500	600 600	1400,1800
INCIDENCE ANGLES	0° – 70°	18° – 59°	17° – 60°	45° & 54°
DAILY COVERAGE	VARIABLE	< 41 %	78 %	92 %
DATA AVAILABILITY	7/78 – 10/78	7/91 – 5/96 & 11/95 –	9/96 – 6/97	7/99 – & 11/00

FIG. 3. The basic characteristics of past and future spaceborne scatterometers. The row labeled resolution gives the nominal spacing of the retrieved wind vectors.

the wave field is rotated by 180°. Winds are retrieved to optimally simulate (by way of the model function) the several scatterometer measurements made of the same earth location.

Because of the nonlinearity of the model function, several wind vectors consistent with the backscatter observations are usually found (Price 1976). These multiple wind vectors are called aliases in the early literature and are now generally referred to as ambiguities. Each ambiguity is assigned a probability of being the closest to the true wind vector. For *ERS-1* and for NSCAT, usually only the first two probabilities are large and the associated ambiguous wind vectors point in nearly opposite directions (Stoffelen and Anderson 1997c). Various filtering approaches (called dealiasing or ambiguity removal algorithms) may then be used to extract a horizontally consistent pattern. Once the ambiguity is removed, the wind vectors chosen are called the selected or unique winds. Collocation studies show that if the ambiguity is properly resolved, scatterometer data are very accurate (Bourassa et al. 1997; Wentz and Smith 1999). Reliably resolving the 180° ambiguity using spatial filters is feasible if a priori information may be used (Golzalez and Long 1999).

Comparisons between scatterometer winds and in situ measurements are fraught with difficulty (Brown 1983). Available ship observations are of poor quality compared to buoys (Pierson 1990), except for some research vessels (Bourassa et al. 1997), when these data are properly processed (Smith et al. 1999). Even buoys are suspect for high winds when wave heights are comparable or exceed the level of the anemometer (Zeng and Brown 1998). Further there are very significant differences between the space and time scales of the scatterometer and buoy wind measurement (Pierson 1983; Austin and Pierson 1999). Finally Freilich (1997) notes that the non-negativity of wind speed contributes to a positive speed bias when comparing wind vectors at low wind speeds, and he proposes a nonlinear regression approach to determine systematic errors and random noise simultaneously.

Freilich and Dunbar (1999) used this methodology to compare NSCAT-1 vector winds with 30 moored National Data Buoy Center buoys. They found that the root-mean-square (rms) speed difference was 1.3 m s^{-1}, and for winds with speeds > 6 m s^{-1}, there were very few (~3%) gross (> 90°) ambiguity removal errors. Excluding gross ambiguity removal errors, they found that the directional differences had a mean of 8° (NSCAT clockwise relative to the buoys) and a standard deviation of 17 . However, it should be noted that Kelly et al. (2001, manuscript submitted to *Geophys. Res. Lett.*) find the largest directional differences with respect to Tropical Atmosphere Ocean (TAO) buoys are associated with very low wind speed and strong currents.

Atlas et al. (1999) compared NSCAT winds to ships and buoys, SSM/I wind speeds, and independent analyses. They report rms wind speed differences of 2.0 m s^{-1} relative to buoys or to the NCEP operational analyses, and 1.4 m s^{-1} relative to SSM/I; and rms wind direction differences of < 20° relative to buoys or to the analyses. Yu and Moore (2000) found NSCAT winds to be higher than TAO buoys and ECMWF analyses while validating the NSCAT winds in the vicinity of the Pacific intertropical convergence zone. Stoffelen (1998) performed triple collocations of in situ, ECMWF forecast, and *ERS-1* winds, with most of the in situ observations from a few towers in the North Sea. Stoffelen's analysis showed that *ERS-1* is biased low by 4% relative to the in situ data, but is more accurate, with standard deviations of wind components for *ERS-1* of ~1.75 m s^{-1} and for in situ data of ~1.95 m s^{-1}.

4. Impact study methodology

As mentioned in the introduction, two types of data impact studies have been conducted to evaluate the effect of satellite surface wind data for NWP. These are *simulation* experiments designed primarily to assess the potential impact of planned satellite observing systems, and *real data* impact experiments to evaluate the actual impact of available space-based data. These two types of experiments are called observing system simulation experiments and observing system experiments, respectively. In the following sections, we summarize some of the main results from scatterometer data impact experiments that have been conducted. But first we describe the general OSSE and OSE methodology. We note that although the basic design of impact experiments is straightforward, these experiments have become increasingly complex and resource demanding, in response to a number of evolving issues described below in our description of the current methodology used for OSSEs.

The basic methodology for OSEs is as follows: First a Control data assimilation is run. This is followed by one or more experimental assimilations in which a particular type of data (or specific observations) is either withheld or added to the Control. Forecasts are then generated from both the Control and experimental assimilations. The analyses and forecasts from each assimilation are then verified and compared in order to determine the impact of each data type being evaluated. Experiments performed in this manner provide a quantitative assessment of the value of a selected type of data to a specific DAS. In addition, the OSE also provides information on the effectiveness of the DAS. This information can be used to improve the utilization of the particular data, as well as other data in the DAS.

In an OSSE the true state of the atmosphere or "nature" is simulated by a long forecast of an NWP model. Simulated "observations" are extracted from the nature run using a suitable geographical and temporal distribution and then observational errors are added. These simulated observations are then assimilated in a DAS using a different forecast model, and forecasts are generated, for various different experimental configurations, as in an OSE. Comparison of the resulting analyses and forecasts with the nature run provides an exact quantitative assessment of the impact of the simulated satellite data within the OSSE context (Fig. 4). Comparison with real data analyses and forecasts enables calibration of the simulation system. The procedure of calibrating OSSEs with OSEs has been used successfully in the planning and evaluation of new observing systems (Atlas et al. 1985,a,b; Hoffman et al. 1990; Rohaly and Krishnamurti 1993).

Since the advent of meteorological satellites in the 1960s, numerous OSSEs and OSEs have been conducted in order to evaluate the impact of these new data sources. The OSEs were conducted to evaluate the impact of specific observations or classes of observations on analyses and forecasts. Such experiments have been performed for selected types of conventional data and for various satellite datasets as they became available (e.g., ECMWF 1990, and references therein). The OSSEs were conducted to evaluate the potential for future observing systems to improve numerical weather predictions (Atlas et al. 1985b; Arnold and Dey 1986; Hoffman et al. 1990). In addition, OSSEs have been used to evaluate trade-offs in the design of observing systems and observing networks (Atlas and Emmitt 1991; Rohaly and Krishnamurti 1993), and to test new methodologies for data assimilation (Atlas and Bloom 1989; Daley 1991).

The current methodology used for OSSEs was designed to increase the realism and usefulness of such experiments (Atlas et al. 1985a):

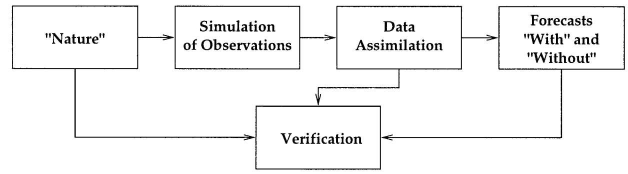

FIG. 4. Schematic of the simulation system.

1) The nature run uses a very high resolution "state of the art" numerical model to provide a complete record of the assumed "true" state of the atmosphere. For the OSSE to be meaningful, it is essential that the nature run be as realistic as possible. The nature run climatology, average storm tracks, etc. should generally agree with observations.
2) Conventional and space-based observations are simulated from the nature run with realistic coverage, resolution, and accuracy. In addition, bias and horizontal and vertical correlations of errors depending on the synoptic situation should be introduced appropriately. Two approaches have been used for this purpose (Atlas et al. 1985; Hoffman et al. 1990). The simpler approach is to interpolate the nature run values to the observation locations and then add appropriate random and systematic errors. The statistics of these errors should agree with estimates from realistic retrieval studies. The more complicated (and expensive) approach is to simulate in some detail the observing system flying over or through the nature run, and then to retrieve observations of the meteorological variables using realistic retrieval methodologies.
3) In order to obtain realistic modeling errors, a different model from that used to generate the nature run is used for assimilation and forecasting. Typically this model has less accuracy and resolution than the nature model.
4) The OSSE is validated and (if necessary) calibrated against a corresponding OSE. For this purpose, the accuracy of analyses and forecasts and the impact of already existing observing systems in the simulation is compared with the corresponding accuracies and data impacts in the real world. Ideally, both the simulated and real results should be similar. Under these conditions, no calibration is necessary and the OSSE results may be interpreted directly. If this is not the case, then calibration of the OSSE results can be attempted by determining the constant of proportionality between the OSE and OSSE impact as described by Hoffman et al. (1990).

The experiments of section 5 suggest that whether scatterometer observations have a positive impact on the subsequent forecast depends to a large extent upon how the data are employed in the DAS. General differences among DASs include quality control procedures; evaluation of the first guess estimate of the observation, including how the first guess is interpolated in time; extent of surface data influence on upper levels; use of the estimated error characteristics; analysis characteristics; multivariate or univariate, spectral or grid point, three-dimensional or four-dimensional; and so forth. In general data impacts depend not only on the new data, but also on the DAS used, and what data are already used by that DAS. In some situations there may be no room for improvement and a new data type may appear redundant. On the other hand with higher resolution, small-scale information in a particular data source, once ignored by the DAS, may become vital. When interpreting and applying impact test results, it must be borne in mind that operational systems continually evolve.

In addition to these general issues of data utilization, there are additional issues specific to scatterometer data. These issues arise because scatterometer data differ from conventional surface wind measurements in a number of important respects, including the following:

- These data are indirect observations, in which a geophysical model function is used to infer surface wind speed and direction from the actual satellite measurements.
- There is directional ambiguity inherent in the measurements. This requires special data checking and quality control procedures.
- The resolution of the satellite observations is tens of kilometers. An anemometer measures the wind at a single location averaged over only a few minutes (Pierson 1983).
- Satellite observations are asynoptic. Binning data into 6-h intervals is a poor approximation, particularly at the surface.

As a result, special analysis techniques have been employed to effectively incorporate satellite observations of oceanic surface winds into surface wind analyses. In addition to addressing the quality control and asynopticity issues mentioned above, analysis approaches have been developed that allow the scatterometer surface wind observations to influence other levels and other variables.

A variety of approaches have been used to account for the special features of scatterometer data in different data assimilation systems. Key features of the GEOS DAS for the quality control and analysis of scatterometer winds are described by Atlas et al. (1999). *ERS-2* data are now used operationally at several centers. The methods used at ECMWF are briefly described below in sections 8 and 9, and in more detail by Stoffelen and Anderson (1997a) and by Isaksen and Stoffelen (2000). *ERS-1,2* data processing at the U.K. Met Office (UKMO) are described by Offiler (1994) and by Andrews and Bell (1998). The Navy Operational Global Analysis and Prediction System (NOGAPS) has been using *ERS-2* scatterometer observations since December 1997 (J. Goerss 2000, personal communication). The NOGAPS system chooses the scatterometer ambiguity closest in direction to the background wind direction. The resulting innovations (observation minus background) are combined into super observations having a 160-km resolution, which are then used in the NOGAPS global analysis (Goerss and Phoebus 1992).

In the NCEP DAS (Kanamitsu 1989; Kanamitsu et al. 1991) scatterometer wind data are assigned the same error characteristics as ship winds. The NCEP DAS is an intermittent assimilation system based on a version of a three-dimensional variational data assimilation scheme (3DVAR) called spectral statistical interpolation (Parrish and Derber 1992). After an extended validation study comparing satellite winds with buoy reports, the *ERS-1,2* winds originally delivered to NCEP by the European Space Agency were found to have unacceptably large wind direction errors. In order to use the data operationally, NCEP now reprocesses the *ERS-2* winds directly from the backscatter measurements following a procedure similar to that of the UKMO (Offiler 1994). For further details and preimplementation test results see Yu et al. (1996).

5. Seasat scatterometer impact studies

In the earliest scatterometer simulation study, Cane et al. (1981) showed substantial positive impacts for the surface pressure and low- and middle-tropospheric wind forecasts (Fig. 5). However several simplifying assumptions were made in that study. First, these were "identical twin" experiments in which the same model was used to generate nature and the forecasts, and thus ignored the effect of model error. Second, the simulated wind observations were at the lowest model level (nominally 945 hPa), not at the surface. Third, no errors or errors with a very simple random statistical structure (and no ambiguity removal errors) were used. As a result of these assumptions, this study overestimated the impact of SASS data. Nevertheless, it did provide a target and an impetus for further research to optimize the use of scatterometer data in NWP.

The SASS impact studies used one of two datasets containing unique winds. These datasets are discussed by Chelton et al. (1989). The first is a subjectively dealiased dataset prepared by meteorologists at the Atmospheric Environment Service, Canada; the Jet Propulsion Laboratory (JPL); and UCLA the University of California, Los Angeles, under the direction of P. Woiceshyn (JPL), following the procedures detailed in Wurtele et al. (1982). This dataset covers the 14-day period beginning 6 September 1978. The second dataset is the objectively dealiased data, which is a byproduct of the study of the surface wind and flux fields by Atlas et al. (1987). This second dataset covers the entire Seasat mission.

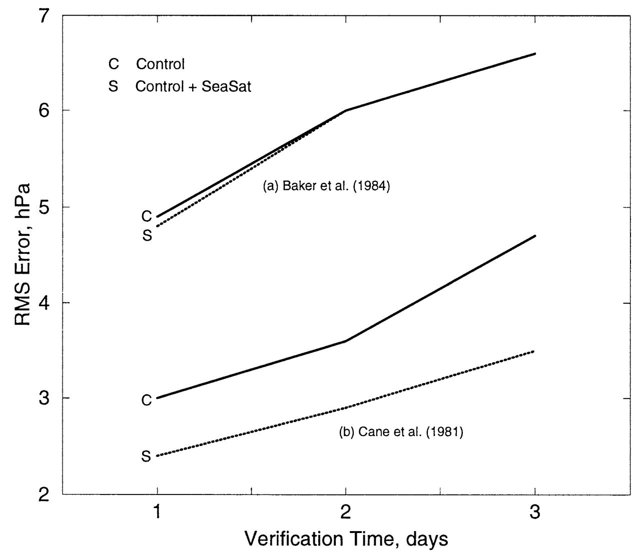

FIG. 5. Rms errors for "real" (from Baker et al. 1984) and "simulated" (from Cane et al. 1981) sea level pressure forecasts for the North Pacific.

In general, the early SASS real data impact studies performed with global models demonstrated potential for the SASS winds to affect surface analyses significantly (Baker et al. 1984; Duffy et al. 1984; Yu and McPherson 1984) but, as illustrated in Fig. 5, failed to show a meaningful improvement in NWP forecasts. Space does not allow a review of the results of all these studies. As an example, at the Goddard Laboratory for Atmospheres (GLA), Baker et al. (1984), using objectively dealiased data, showed a negligible effect of the SASS data in the Northern Hemisphere extratropics. In the Southern Hemisphere extratropics, the SASS data were found to have a positive effect on the analyses and forecasts, but the effect was smaller than that of Vertical Temperature Profile Radiometer (VTPR) data; the impact of the SASS data was reduced when VTPR soundings were utilized, indicating some redundancy between the two datasets. On occasion, large impacts due to SASS in the analyses and forecasts were noted over the Southern Hemisphere extratropical oceans even when VTPR data were present. However, verification in these regions is difficult.

Results similar to those obtained by Baker et al. (1984) were reported by some later investigators as well: Anderson et al. (1991a,b), using the subjectively dealiased data, demonstrated some speed-dependent biases between SASS and the model and some directional irregularities. Overall they found small impacts in the Northern Hemisphere extratropics and substantial impacts in the Southern Hemisphere extratropics analyses. Ingleby and Bromely (1991), using objectively dealiased data, found large changes to Southern Hemisphere extratropics analyses, but only small forecast impacts. They tested different vertical correlation functions in the analysis, and also noted that the data at the edge of the swath tends to be less accurate, but nevertheless is very important because it influences the analysis beyond the swath.

A number of factors have been suggested as limiting the impact on the model prediction in one or more of the early studies. These include the coarse resolution of the models used, the failure to explicitly resolve the planetary boundary layer, ambiguity and other errors in SASS winds, the inability to account for these errors properly, the treatment of SASS data as synoptic, the lack of or inappropriate coupling of surface wind data to higher levels, and data redundancy.

In an attempt to understand the disagreement between the SASS OSSE and OSE results, we conducted several idealized simulation experiments. In the first of these experiments Atlas and Pursch (1983) generated forecasts from initial conditions in which the correct 1000-hPa or 1000- and 850-hPa wind fields were replaced by the corresponding fields from 24 h earlier. The results indicated that the model forecast was sensitive to surface wind data where large analysis errors were present and that the effect of SASS data would be enhanced if higher levels were accurately affected in the analysis.

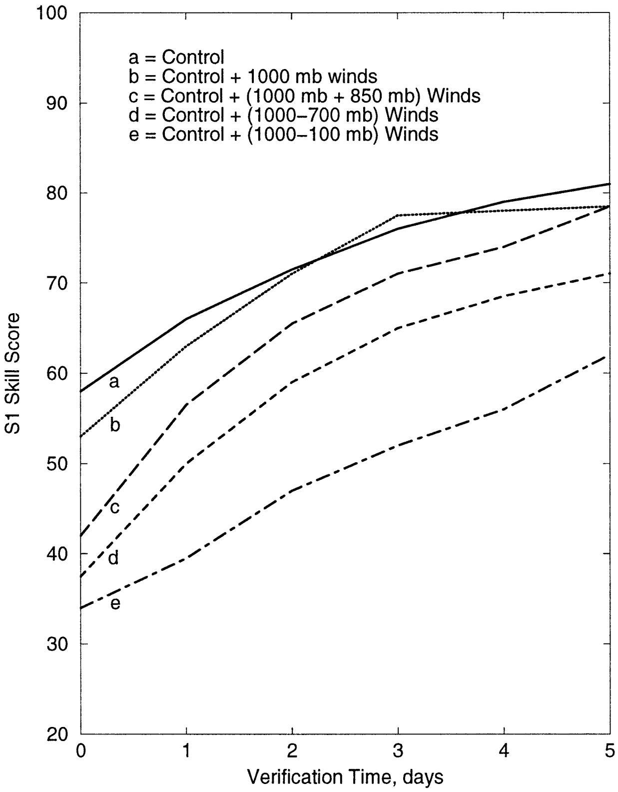

FIG. 6. Forecast sea level pressure S1 skill scores for different amounts of vertical extension of surface wind data. See text for a description of the experiments.

In further simulation experiments, Atlas et al. (1986) added wind data at the Television Infrared Observation Satellite-N (TIROS-N) locations to a control experiment in which only simulated conventional data were assimilated. The control experiment is described in detail by Atlas et al. (1985b). The wind data were perfect and either added at the surface (1000 hPa), in the lower boundary layer (1000, 850 hPa), in the entire boundary layer (1000, 850, 700 hPa), or throughout the troposphere (all mandatory levels within 1000–100 hPa). The last experiment allows comparison of a scatterometer with a notional lidar wind profiler. Figure 6 shows the impact of the wind data on the S1 skill scores (Teweles and Wobus 1954) for sea level pressure over the Southern Hemisphere extratropics, for a single forecast. In reality the surface winds observed by a scatterometer are imperfect and the extension of these winds to higher levels would also be imperfect. Still, these experiments suggested that the impact of surface wind data on the analyses and forecasts could be significantly enhanced if procedures were developed to accurately extend their influence through the boundary layer.

As an application of these results, Duffy and Atlas (1986) used characteristics of the synoptic situation to extend the vertical influence of subjectively dealiased SASS winds in a regional modeling experiment of the famous storm that damaged the *Queen Elizabeth II* (*QE II*) oceanliner on 10 September 1978. Duffy and Atlas showed that the use of SASS winds resulted in a significant improvement in the prediction of this intense storm. Duffy and Atlas found that data inserted at a single level had little effect. In more recent experiments, results similar to the positive impacts obtained by Duffy and Atlas were also found in the regional modeling study of Stoffelen and Cats (1991) and in the global model experiments presented by Atlas (1988) and Lenzen et al. (1993). Stoffelen and Cats used the subjectively selected ambiguities for the *QE II* and *Ark Royal* cases, and found substantial analysis impacts and small positive forecast impacts. The analysis impacts they observe suggest that the scatterometer data can provide useful information on the small scale that is otherwise not observed.

6. *ERS-1* and NSCAT OSSEs

The SASS studies demonstrated that satellite surface wind data have great potential to improve ocean surface analysis and numerical weather prediction, and suggest that improved surface wind velocity data from advanced scatterometers such as *ERS-1,2,* NSCAT, and SeaWinds would result in an even larger improvement. In order to assess the magnitude of this potential improvement, an OSSE was conducted in the late 1980s as a follow-up to a joint NASA–National Oceanic and Atmospheric Administration–ECMWF OSSE evaluating the relative impact of temperature and wind profiles (Atlas et al. 1985a).

In this experiment, the nature run was generated by ECMWF as an extended forecast of the T106 version of the operational model (Simmons et al. 1989). It was evaluated at the Goddard Space Flight Center (GSFC) and found to be sufficiently realistic. Simulated conventional data and satellite temperature soundings were generated at NCEP, and *ERS-1* scatterometer wind vectors and NSCAT wind vectors meeting the accuracy requirements given by Table 2 were generated at GSFC. Assimilations and forecasts using various combinations of simulated data in the GEOS-1 system were then performed and evaluated.

Figure 7 summarizes the resulting impact of the different types of satellite data on surface wind analy-

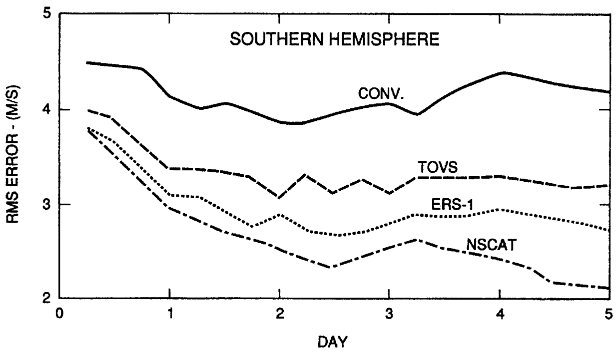

FIG. 7. Rms analysis errors for the different OSSEs described in the text over 5 days of assimilation in the Southern Hemisphere extratropics. Experiment TOVS is approximately equivalent to the control experiment in other figures. [After Atlas (1997a).]

ses in the Southern Hemisphere extratropics over a period of 5 days of data assimilation. Shown in the figure are the accuracy of analyses using only conventional data (CONV), CONV plus satellite temperature soundings (TIROS Operational Vertical Sounder, TOVS), TOVS plus *ERS-1* surface winds (*ERS-1*), and TOVS plus NSCAT winds instead of *ERS-1* data (NSCAT). Note that the TOVS experiment is equivalent to the Control experiment in the OSEs described in the following sections. For the results presented here and below, 20° of latitude marks the separation between the Tropics and the extratropics. This figure shows that the assimilation of satellite temperature soundings results in a very significant decrease in surface wind analysis errors; the addition of *ERS-1* winds reduces this error further; but the assimilation of NSCAT data would have approximately twice the impact of *ERS-1* data and result in analysis errors averaged over the Northern Hemisphere extratropics and Southern Hemisphere extratropics that are within 2.25 m s^{-1} rms error limits after 5 days of assimilation. This is due primarily to the better coverage of NSCAT. Figure 8 presents the relative impact of NSCAT and *ERS-1* winds on sea level pressure forecasts and indicates that, relative to the TOVS experiment, the useful forecast range for this model could be extended by more than 1 day using NSCAT data.

Later real data experiments described in the following sections gave very similar results to these OSSEs. This is in marked contrast to the early comparisons between the OSSEs and OSEs for SASS, and is evidence that current OSSEs can overcome the various issues described in section 4. These OSSEs also helped to design improvements to GEOS-2 to take account of the asynopticity of the scatterometer datasets.

7. Impact of *ERS-1*

Several different experiments have been conducted to evaluate the utility of *ERS-1* scatterometer winds in data assimilation. At GSFC, we conducted a series of OSEs to evaluate the impact of *ERS-1* scatterometer data on model analyses and forecasts of the GEOS-1 DAS and the NCEP DAS that was operational in 1995 (NCEP95). The initial experiments that we performed used the 4° × 5° latitude–longitude grid version of GEOS-1 and were designed to assess the relative utility of ESA and JPL *ERS-1* winds and to evaluate the contribution of the directional information in the JPL winds. Later experiments, using GEOS-1 at a resolution of 2° × 2.5° and the NCEP95 system truncated at 62 waves (T62), were conducted to evaluate the impact of five different retrieval methods. Additional experiments were conducted to assess the impact of winds resulting from the direct utilization of backscatter measurements in a variational analysis.

Table 3 summarizes the *ERS-1* experiments that were performed. The GEOS-1 4° × 5° experiments, listed at the top of Table 3, were our initial tests of *ERS-1* conducted in 1993. Five assimilations with four forecasts from each were generated. These included the Control, which used all conventional data plus satellite temperature soundings (SATEM) and cloud track winds (CTWs); ESA, which added ESA operational surface wind vectors to the control; JPL, which added JPL-selected surface wind vectors to the control; ALIAS, which added ambiguous JPL wind vectors, choosing the ambiguity closest to the model first guess; and SPEED, which added JPL wind speeds only.

Figure 9 shows the average impact of each of these datasets on GEOS-1 500-hPa height forecasts for the Southern Hemisphere extratropics. Both the JPL and

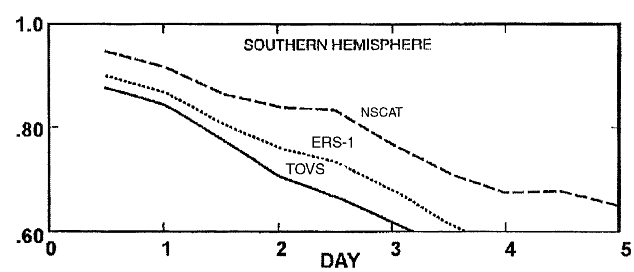

FIG. 8. Anomaly correlation scores for sea level pressure forecasts from the GEOS-1 model for the Southern Hemisphere extratropics, based on assimilations that exclude satellite surface wind velocity data (TOVS) and include either simulated *ERS-1* scatterometer data or NSCAT data.

TABLE 3. Experiments for *ERS-1* using the GEOS-1 4° × 5° DAS, the GEOS-1 2° × 2.5° DAS, and the NCEP95 T62 DAS.

GEOS-1 4° × 5°	Spinup	1200 UTC 25 Feb–0300 UTC 1 Mar 1993
	Assimilations	0300 UTC 1 Mar–0300 UTC 21 Mar 1993
	• Control	All conventional data plus SATEM plus CTW
	• ESA	Control plus ESA scatterometer wind vectors
	• JPL	Control plus JPL scatterometer wind vectors
	• ALIAS	Control plus ambiguous JPL scatterometer wind vectors
	• SPEED	Control plus JPL scatterometer wind speeds
	Forecasts	6, 11, 16, 21 Mar
GEOS-1 2° × 2.5°	Spinup	1200 UTC 25 Feb–0300 UTC 1 Mar 1993
	Assimilations	0300 UTC 1 Mar–0300 UTC 24 Mar 1993
	• Control	All conventional data plus SATEM plus CTW
	• ESA	Control plus ESA scatterometer wind vectors
	• JPL	Control plus JPL scatterometer wind vectors
	• NCEP	Control plus NCEP scatterometer wind vectors
	• GLA	Control plus GLA scatterometer wind vectors
	Forecasts	6, 11, 16, 21 Mar
	Assimilations	0300 UTC 1 Mar–0300 UTC 6 Mar 1993
	• VAR	Control plus VAR scatterometer wind vectors
	Forecasts	6 Mar
NCEP95 T62	Spinup	1200 UTC 25 Feb–0000 UTC 1 Mar 1993
	Assimilations	0000 UTC 1 Mar–0300 UTC 26 Mar 1993
	• Control	All conventional data plus SATEM plus CTW
	• ESA	Control plus ESA scatterometer wind vectors
	• JPL	Control plus JPL scatterometer wind vectors
	• NCEP	Control plus NCEP scatterometer wind vectors
	Forecasts	6, 11, 16, 21 Mar

ESA winds show a substantial positive impact on GEOS-1 model forecasts in the Southern Hemisphere extratropics, although in general the ESA winds yield higher forecast accuracy. Comparison of the JPL, ALIAS, and SPEED curves shows that both the directional and speed information of *ERS-1* are contributing to improve the analyses and forecasts of GEOS-1. In the Northern Hemisphere extratropics and Tropics (not shown) the impact of *ERS-1* on GEOS-1 model forecasts was found to be negligible.

The GEOS-1 2° × 2.5° experiments, listed in the middle of Table 3, consisted of a Control assimilation and assimilations that added either ESA, JPL, NCEP, or GLA *ERS-1* scatterometer wind vectors to the Control. NCEP and GLA *ERS-1* winds were generated at GSFC using modified UKMO wind retrieval methodology and either the operational NCEP analysis as the background or the GEOS-1 control analysis (defined below) as the background. Four forecasts were generated from each of these assimilations. A shorter experimental assimilation (VAR) and a single forecast were generated in which scatterometer winds were first retrieved at GSFC by utilization of *ERS-1* backscatter measurements [as was done by Thèpaut et al. (1993)] in a 2DVAR analysis (Hoffman 1984), using the GEOS-1 Control analysis as the background, and then assimilated using the GEOS-1 DAS.

Figure 10 shows the average impact of the ESA, JPL, NCEP, and GLA *ERS-1* datasets on GEOS-1 2° × 2.5° forecasts of 500-hPa height for the Southern Hemisphere extratropics. Each of the *ERS-1* datasets yields a significant improvement in forecast accuracy in this region, but in agreement with the 4° × 5° results, no improvement in forecast accuracy occurs in the Tropics or Northern Hemisphere extratropics.

A detailed synoptic evaluation of each of the above assimilations and forecasts was performed in order to better understand the nature and significance of the above impacts. This evaluation showed substantial modifications to ocean surface winds and to the baroclinic structures above the boundary layer in the free atmosphere. These modifications resulted in a significant impact on cyclone prediction in the South-

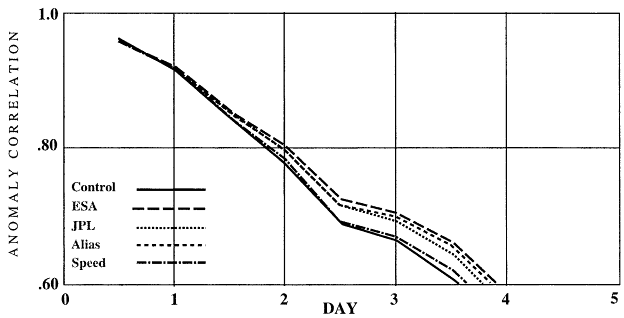

FIG. 9. Anomaly correlation of the 4° × 5° GEOS-1 forecasts for 500-hPa heights in the Southern Hemisphere extratropics averaged over four cases. Experiments as described in Table 3.

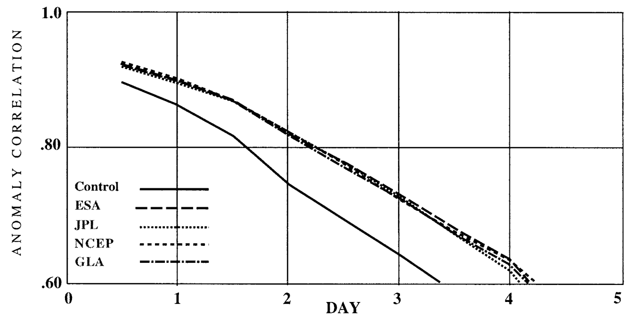

FIG. 10. Anomaly correlation of the 2° × 2.5° GEOS-1 forecasts for 500-hPa heights in the Southern Hemisphere extratropics averaged over four cases. Experiments as described in Table 3.

ern Hemisphere extratropics. Overall, cyclone displacement and development were improved significantly by the assimilation of *ERS-1* winds (Terry and Atlas 1996). However, occasional examples of significant negative impact were also observed. The limited VAR experiment was an effort to reduce the occurrence of negative impacts and improve the accuracy and spatial coherence of the *ERS-1* winds. Comparison of VAR and GLA winds (not shown), which used the same background field, reveals clear examples of improved wind directions in the VAR, as judged by meteorological reasonableness and agreement with imagery. In particular the VAR is able to shift cyclone positions. Figure 11 shows the improvement in forecast accuracy that resulted from the use of the VAR.

The NCEP95 T62 experiments, listed at the bottom of Table 3, consist of a Control, which included all data except for satellite surface winds; and experiments that add JPL, ESA, or NCEP *ERS-1* surface wind data. Figure 12 presents the average impact of these data sets on the NCEP95 T62 model forecasts of 50-hPa height for the Southern Hemisphere extratropics. From this figure it can be seen that for this model *ERS-1* had a positive forecast impact, and that the UKMO wind retrievals with the operational NCEP analysis as the background field give somewhat better results than the other retrievals. The comparison of these results with those for GEOS-1 (Fig. 10) indicates that the impact of *ERS-1* data is similar in both systems. In addition, the synoptic evaluation of the NCEP95 T62 forecasts revealed a comparable impact on cyclone prediction.

Hoffman (1993) reported on a preliminary study of *ERS-1* winds on the ECMWF global DAS. This study, which used an early version of *ERS-1* scatterometer winds, found substantial modifications to surface wind analyses. However, forecast impacts were neutral, with no consistent improvement or degradation. Several 4DVAR experiments with and without *ERS-1* backscatter measurements were also conducted (Thèpaut et al. 1993). For scatterometer data, the advantage of the variational approach is that it embeds the ambiguity problem in a large data fitting problem that includes other observations, a back-

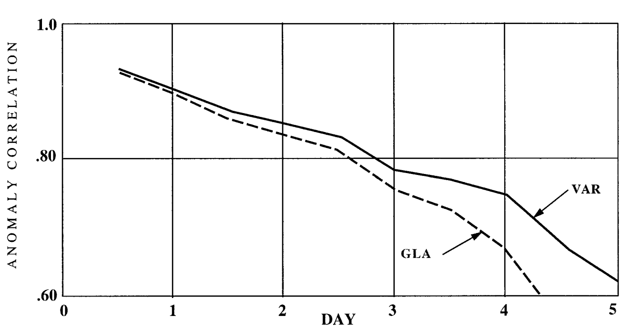

FIG. 11. Anomaly correlation of the VAR and GLA 2° × 2.5° GEOS-1 forecasts for 500-hPa heights in the Southern Hemisphere extratropics for the case of 6 Mar 1993. Experiments as described in Table 3.

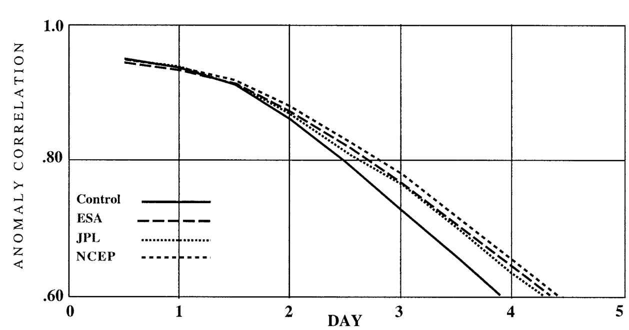

FIG. 12. Anomaly correlation of the NCEP95 T62 forecasts for 500-hPa heights in the Southern Hemisphere extratropics averaged over four cases. Experiments as described in Table 3.

ground constraint based on balanced error covariances, and the model dynamics. The last two factors lead necessarily to a dynamically consistent use of the data. As expected and in contrast to conventional approaches, the analysis increments due to scatterometer data in 4DVAR are less localized and more baroclinic (i.e., tilt in the vertical).

The assimilation experiments of Thèpaut et al. (1993) are for a 24-h period during which a violent storm struck the coast of Norway. These experiments showed a large impact of the *ERS-1* data in the Southern Hemisphere extratropics, with differences of up to 10 hPa in the surface pressure field. Substantial differences were also observed in the Northern Hemisphere extratropics, especially in the North Atlantic. Generally the *ERS-1* data strengthened the activity of the affected systems. The impacts on the analysis and forecast of the storm that struck Norway are small but the scatterometer data did have an apparently positive impact on the 4DVAR analysis in this case.

Stoffelen and Anderson (1997a) studied the impact of improved *ERS-1* winds on a more recent operational version of the ECMWF DAS. In this version, a special scatterometer observation operator makes use of two ambiguities at each scatterometer location and effectively chooses one during the 3DVAR minimization procedure. If there are more than two ambiguities at one location, the most likely ambiguity and the one most nearly opposite in direction are used. In these experiments, analyses were clearly improved, but there was no significant improvement in forecast accuracy beyond 12 h. In contrast, the results reported below and those reported by Andrews and Bell (1998), who used the UKMO global DAS, show substantial improvement in analysis and forecast accuracy in the Southern Hemisphere extratropics when *ERS-1* wind vectors are assimilated.

More recent studies at ECMWF showed a favorable impact of *ERS-1* data on tropical cyclone analyses and forecasts in the 3DVAR system (Andersson et al. 1998; Tomassini et al. 1998), and demonstrated positive impact of ERS scatterometer data on tropical cyclone forecasting in the 1–5-day forecast range using 4DVAR and the two ambiguity cost functions (Isaksen et al. 1998; Isaksen and Stoffelen 2000). Finally experiments have been conducted at ECMWF (Le Meur et al. 1997) and the Royal Netherlands Meteorological Institute (KNMI; Stoffelen and van Beukering 1997) demonstrating the synergistic impact of using both the *ERS-1* and *ERS-2* scatterometers simultaneously.

8. Impact of NSCAT

At the DAO, GEOS-1, and GEOS-2 model forecasts were performed as a component of the overall validation of NSCAT winds. A Control assimilation was generated using all available data (conventional surface data, rawinsondes, aircraft observations, satellite temperature soundings, and cloud-drift winds) with the exception of satellite surface winds. Then assimilations were generated that added either SSM/I wind speeds, NSCAT wind speeds (NSCAT-S), or NSCAT unique wind vectors in which model fields are used to initialize the median filter used for ambiguity removal. The NCEP model fields used therefore have a weak influence on these "nudged" unique winds (NSCAT-N). The experiments that were performed are summarized in Table 4.

For each experiment, an assimilation for nearly 2 months was performed and then eight independent numerical forecasts were generated (from initial states obtained at approximate 5-day intervals within the 2-month assimilation period). Objective measures of forecast accuracy, including anomaly correlation, rms error, and S1 skill score, were calculated for a wide range of prognostic variables from each of these experiments. For brevity, only the sea level pressure anomaly correlations for the averages over all eight forecasts are presented for the Northern Hemisphere extratropics and Southern Hemisphere extratropics

TABLE 4. NSCAT experiments using the GEOS-1 DAS. (Note that NSCAT-N and NSCAT-S are comparable to the *ERS-1* experiments JPL and SPEED.)

GEOS-1 $2° \times 2.5°$	Spinup	0300 UTC 10 Sep–0300 UTC 15 Sep 1996
	Assimilations	0300 UTC 15 Sep–0300 UTC 12 Nov 1996
	• Control	All conventional data plus SATEM plus CTW
	• SSM/I	Control plus SSM/I wind speeds
	• NSCAT-N	Control plus NSCAT nudged wind vectors
	• NSCAT-S	Control plus NSCAT wind speeds
	Forecasts	Eight cases

(Fig. 13). Further details of these experiments, including a description of the evolution of the impact of NSCAT-N in the GEOS-1 DAS, are presented in Atlas et al. (1999).

From Fig. 13, it can be seen that in the Northern Hemisphere extratropics there is on average virtually no difference between any of the forecasts scores. However, a very significant positive impact of NSCAT data is evident in the Southern Hemisphere extratropics. The assimilation of the NSCAT-N unique wind vectors results in a large increase in anomaly correlation relative to the Control for days 2–5 of the forecast. In addition, the 5-day NSCAT-N forecast is more accurate than the 4-day Control forecast (without NSCAT data). These results help to validate the NSCAT data and indicate that the impact of NSCAT data on ocean surface wind analyses is overwhelmingly positive. The use of either the SSM/I or NSCAT-S winds also results in a significant improvement in forecast accuracy in the Southern Hemisphere extratropics. For both datasets the impact is about half that of the NSCAT-N impact through most of the forecast period. This indicates the usefulness of the NSCAT directional information. Considering the greater coverage of SSM/I, the results indicate that the NSCAT wind speeds are at least of comparable utility as the SSM/I wind speeds.

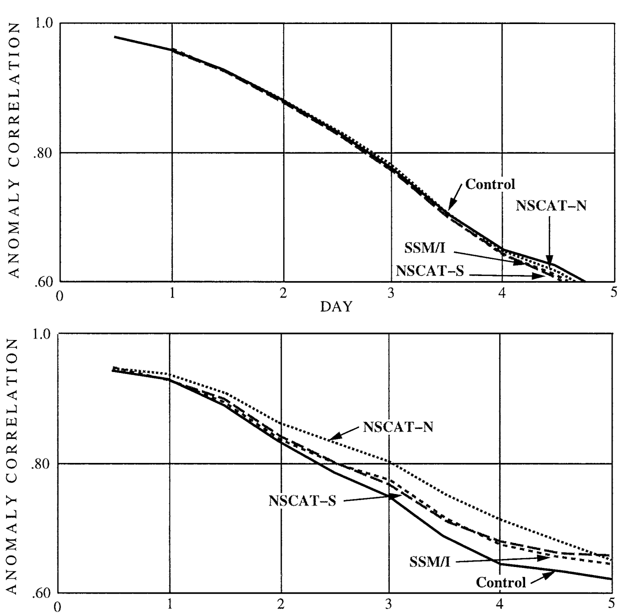

FIG. 13. Relative impact of NSCAT-N, NSCAT-S, and SSM/I data on 2° × 2.5° GEOS-1 model forecasts. The sea level pressure anomaly correlations, averaged over eight forecasts, are shown for the (top) Northern Hemisphere extratropics and (bottom) Southern Hemisphere extratropics. Experiments as described in Table 4.

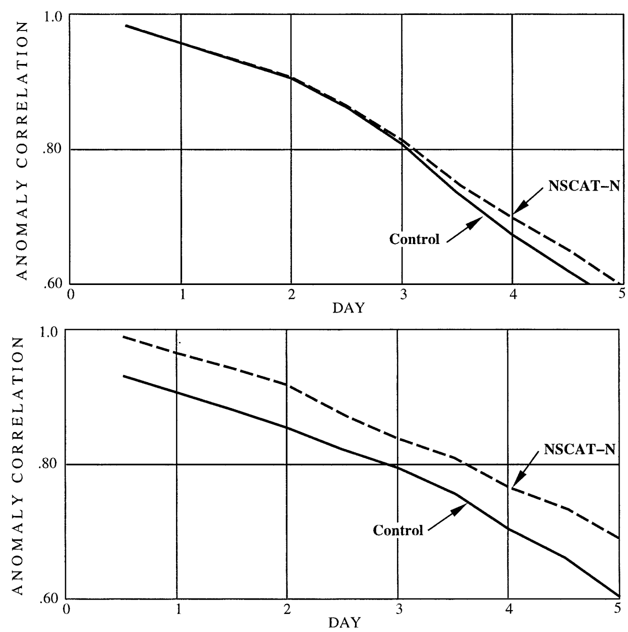

FIG. 14. Relative impact of NSCAT-N data on GEOS-2 2° × 2.5° model forecasts. As in Fig. 13.

It should be noted that SSM/I wind retrievals are not available in areas of rain or significant water cloud—just the areas needed to analyze fronts and cyclones.

These results are particularly significant because the OSSEs of section 6 conducted prior to the launch of NSCAT predicted very similar results. The most significant discrepancy between the OSSEs and the OSEs is the lack of any impact on average in the Northern Hemisphere extratropics in the OSEs. This discrepancy is due in part to one of the simplifying assumptions of the simulation study. In that experiment, NSCAT data were simulated as being synoptic, that is, at 6-h intervals, with no time displacement from the analysis times. Therefore in the simulation study, there was no error associated with assimilating the data in 6-h increments. This suggested to the authors that taking account of the asynopticity of the NSCAT winds would improve the impact in the Northern Hemisphere extratropics. To this end, in the GEOS-2 DAS, the NSCAT observation increments are calculated using the first guess at the time of the observation.

Figure 14 summarizes the impact of unique NSCAT wind vectors using the GEOS-2 DAS. Comparing Fig. 14 to Fig. 13 shows that the Control forecast accuracy is improved significantly relative to GEOS-1. In fact the 3-day Control forecast accuracy with GEOS-2 is equal to the 3-day NSCAT-N accuracy with GEOS-1. Despite this substantial improvement

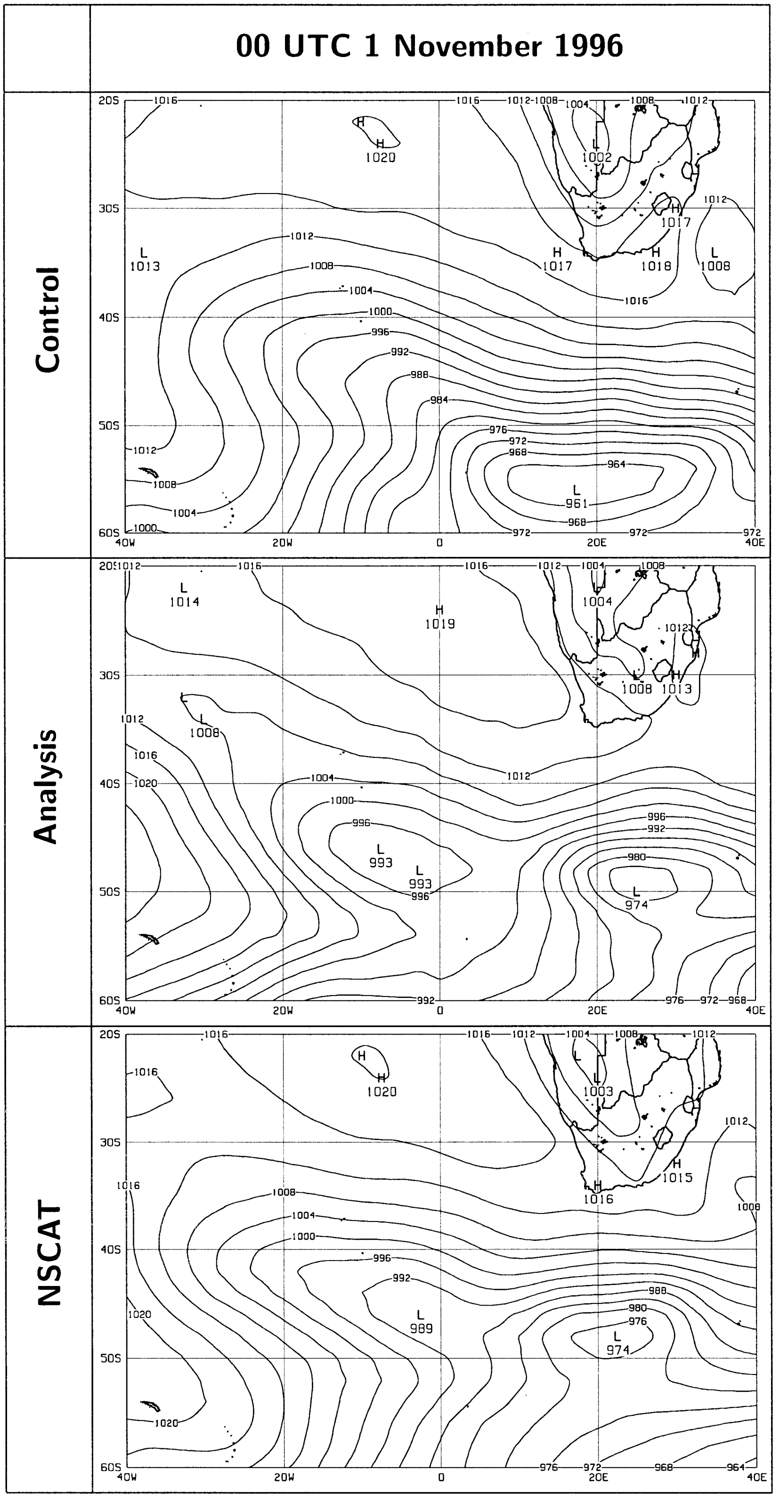

FIG. 15. The 96-h (top) Control and (bottom) NSCAT-N GEOS-1 sea level pressure forecasts for a portion of the Southern Hemisphere extratropics, and (middle) the verifying Control analysis at 0000 UTC 1 Nov 1996.

in the Control, the impact of NSCAT data in the Southern Hemisphere extratropics with GEOS-2 is comparable to the impact obtained with GEOS-1. In both systems, a 24-h extension of useful forecast skill results from the assimilation of NSCAT winds. In the Northern Hemisphere extratropics, a much more modest, but nevertheless positive impact of NSCAT data is obtained with the GEOS-2 DAS.

We now present two synoptic cases to illustrate the impact of scatterometer data on NWP. In both cases, the impact of NSCAT unique winds will be shown. It should be noted that the assimilation of either ERS or SSM/I surface wind data can result in similar impacts. However, the impact of NSCAT was in general larger and more frequent.

Figure 15 shows an example of the impact of NSCAT winds on the prediction of sea level pressure in the Southern Hemisphere extratropics, using the GEOS-1 DAS. In the figure, the GEOS-1 96-h Control and NSCAT-N forecasts from 0000 UTC 28 October 1996, and the corresponding verification are shown for a portion of the Southern Hemisphere extratropics. Comparison of the forecasts with the verifying analysis shows a very significant improvement to the cyclonic circulation over this area due to the influence of NSCAT data. In particular, the central pressure and structure of the intense cyclone south of Africa near 48°S, 25°E is improved very substantially, and its position error is reduced by over 500 km. (In the NSCAT experiment this low is at 48°S, 22°E just west of the analyzed low, while in the Control experiment this low is at 55°S, 18°E far to the south and west.) Other improvements include the formation of the weaker cyclone near 47°S, 5°W, and the representation of the sea level pressure ridge to the southwest of this cyclone. Impacts such as this are typical in the Southern Hemisphere extratropics in each of the data assimilation systems examined.

A second illustration, presented in Fig. 16, shows the impact of NSCAT data over the North Pacific, using the GEOS-2 DAS. This figure shows 60-h sea level pressure forecasts generated from the Control assimilation, as well as

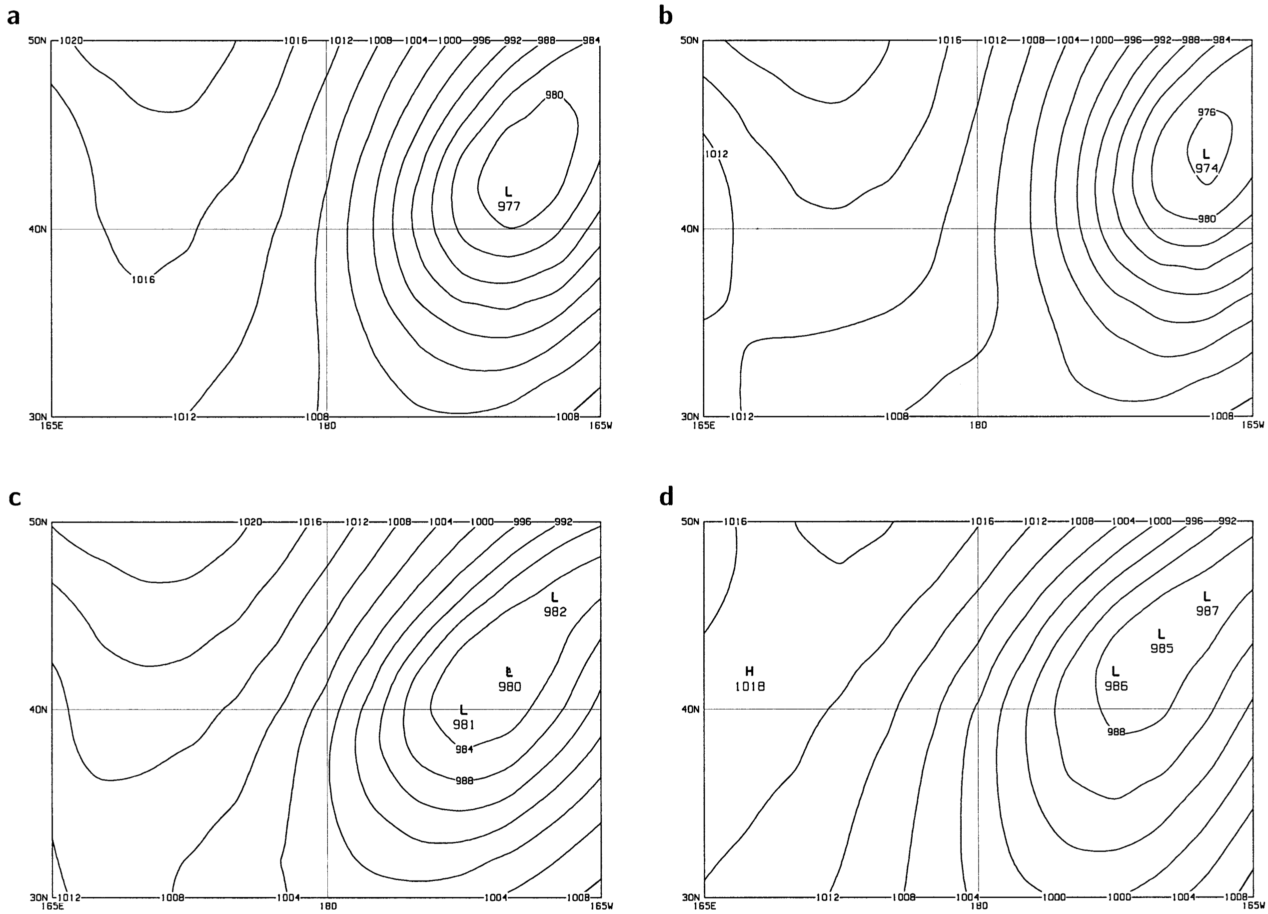

FIG. 16. The GEOS-2 60-h sea level pressure forecasts for the North Pacific (a) generated without NSCAT data, (b) with NSCAT data assimilated synoptically in 6-h bins centered on the analysis time, and (c) with NSCAT data assimilated asynoptically. (d) The ECMWF sea level pressure analysis at 1200 UTC 24 Sep 1996.

from corresponding experiments in which NSCAT data are assimilated either asynoptically or synoptically. The ECMWF sea level pressure analysis for the same time (1200 UTC 24 Sep 1996) is presented for verification. Comparison of these figures shows that the 60-h forecast with NSCAT data treated asynoptically is a significant improvement over the other predictions. In this case, when NSCAT is treated synoptically, the time displacement of the NSCAT data relative to the analysis time results in an incorrect prediction of the cyclone. In effect, accurate data used at the wrong time lead to a negative impact. In contrast, the asynoptic assimilation effectively uses the available scatterometer observations to predict the location and structure of the cyclone accurately.

A series of data assimilation experiments were conducted to test the impact of NSCAT wind data in the NCEP global DAS (Peters 1999). Two NSCAT wind datasets were tested: one was the so-called fast delivery dataset operationally available in the NCEP global observation database, and the other the so-called science dataset produced by NASA JPL for early impact testing. The assimilation and forecast experiments, similar in design to those of Yu et al. (1996), were conducted for a period of 16 days during the months of May and June 1997. A total of 11 forecasts were made during the assimilation period. The results indicate that the NSCAT wind data had a small positive impact in the Southern Hemisphere extratropics as seen in the 1000- and 500-hPa anomaly correlation scores, but in the Northern Hemisphere extratropics the impact was neutral. The results also show that in terms of impacts on the NCEP assimilation and forecast systems, there was little difference between the fast delivery and science dataset.

In preparation for the arrival of QuikSCAT data, NSCAT data were used in ECMWF's 4DVAR assimilation system to assess the impact of a Ku-band scatterometer on analyses and forecasts. In these experiments the forecast model resolution was T319 and

31 layers. The analysis increments were restricted to T63 resolution. OSEs were performed for a combined period of 1 month during September and October of 1996. NSCAT 50-km wind ambiguities produced by JPL were used in the experiments. No *ERS-2* data were used in order to isolate the impact of NSCAT winds. The misfit of the analyses to the NSCAT data were computed using a two-ambiguity cost function as previously described for ERS: at each location the most likely NSCAT wind ambiguity and the ambiguity most nearly opposed in direction are presented to the 4DVAR, which then effectively performs ambiguity removal as part of the data assimilation. If the separation in direction between the two ambiguities is < 135°, then the wind vector cell is not used. Additional quality control includes high wind speed and sea ice checks.

These preliminary NSCAT experiments at ECMWF showed only small positive and negative impacts on global and hemispheric measures of forecast skill. Nevertheless, NSCAT data frequently make significant changes to subsynoptic-scale features in the analyses. The most common changes are seen in the placement of cyclones and anticyclones, particularly in the Tropics and Southern Hemisphere extratropics. Figure 17 shows a dramatic impact on the placement of Hurricane Lili in the central Atlantic. The top panels of Fig. 17 show the position of Lili in the first guess at 0000 UTC 26 October. (In this case, both analyses started from the same first guess fields.) The middle panels show the analyzed position of Lili, and the bottom panels show the increments in sea level pressure and winds. While Lili is still much too weak in both analyses, the NSCAT analysis demonstrates a great improvement in position and a modest improvement in intensity. The impact in this case is unusually large compared to typical impacts around cyclones, but demonstrates how effective these data can be. No forecast was made from this analysis, but in the next forecast, made at 1200 UTC, Lili reached the Irish coast in 48 h. In the NSCAT experiment, the forecast minimum pressure of Lili at landfall (974 mb) was within 1 mb of the observed (973 mb), while in the experiment without scatterometer data (NoSCAT), the forecast intensity was too weak (979 mb).

9. Impact of SeaWinds

In this section, we report briefly on preliminary experiments to assess the impact of SeaWinds data from QuikSCAT on NWP. The QuikSCAT surface winds from the initial JPL science data products were evaluated as part of a collaborative project between the Environmental Modeling Center of NCEP, NESDIS, and the DAO. The first component of this evaluation consisted of both subjective and objective comparisons of QuikSCAT winds to ship and buoy observations, GEOS and NCEP wind analyses, *ERS-2* wind vectors, and SSM/I wind speeds. This was then followed by a series of data assimilation and forecast experiments using the GEOS and operational NCEP DASs. The experiments were aimed at comparing the impact of QuikSCAT with that previously obtained with NSCAT, and assessing the relative utility of QuikSCAT, SSM/I, and *ERS-2* winds, the relative contributions of QuikSCAT directional and speed information, and the effectiveness of the QuikSCAT ambiguity removal algorithms.

For each DAS used, a Control assimilation was generated using all available data with the exception of satellite surface winds. Then assimilations were generated that added either SSM/I wind speeds, QuikSCAT wind speeds, *ERS-2* unique wind vectors, QuikSCAT ambiguous wind vectors, QuikSCAT unique wind vectors, or the combination of QuikSCAT with *ERS-2* and SSM/I. The results of this initial evaluation of QuikSCAT demonstrated potential for QuikSCAT data to improve meteorological analyses and forecasts, but also indicated ambiguity removal, and rain contamination problems that were limiting the application of QuikSCAT winds to data assimilation. Each of these components of the wind retrieval for QuikSCAT are being improved at the time of this writing (e.g., Huddleston and Stiles 2000; Jones et al. 2000; Mears et al. 2000; Stiles et al. 2001, manuscript submitted to *IEEE Trans. Geosci. Remote Sens.*).

As an illustration of the impact of QuikSCAT data, Fig. 18, shows anomaly correlations for a limited sample of GEOS-3 Control and QuikSCAT 500-hPa height forecasts for the Northern Hemisphere extratropics and Southern Hemisphere extratropics. From this figure, it can be seen that there is a slight positive impact of QuikSCAT in the Northern Hemisphere extratropics and a larger positive impact in the Southern Hemisphere extratropics using this DAS. These results may change somewhat as the quality of SeaWinds data improve and as the sample size increases.

Limited OSEs have also been conducted at ECMWF with QuikSCAT data. In these experiments the forecast model resolution was T319 and 60 layers. The analysis increments were restricted to T63

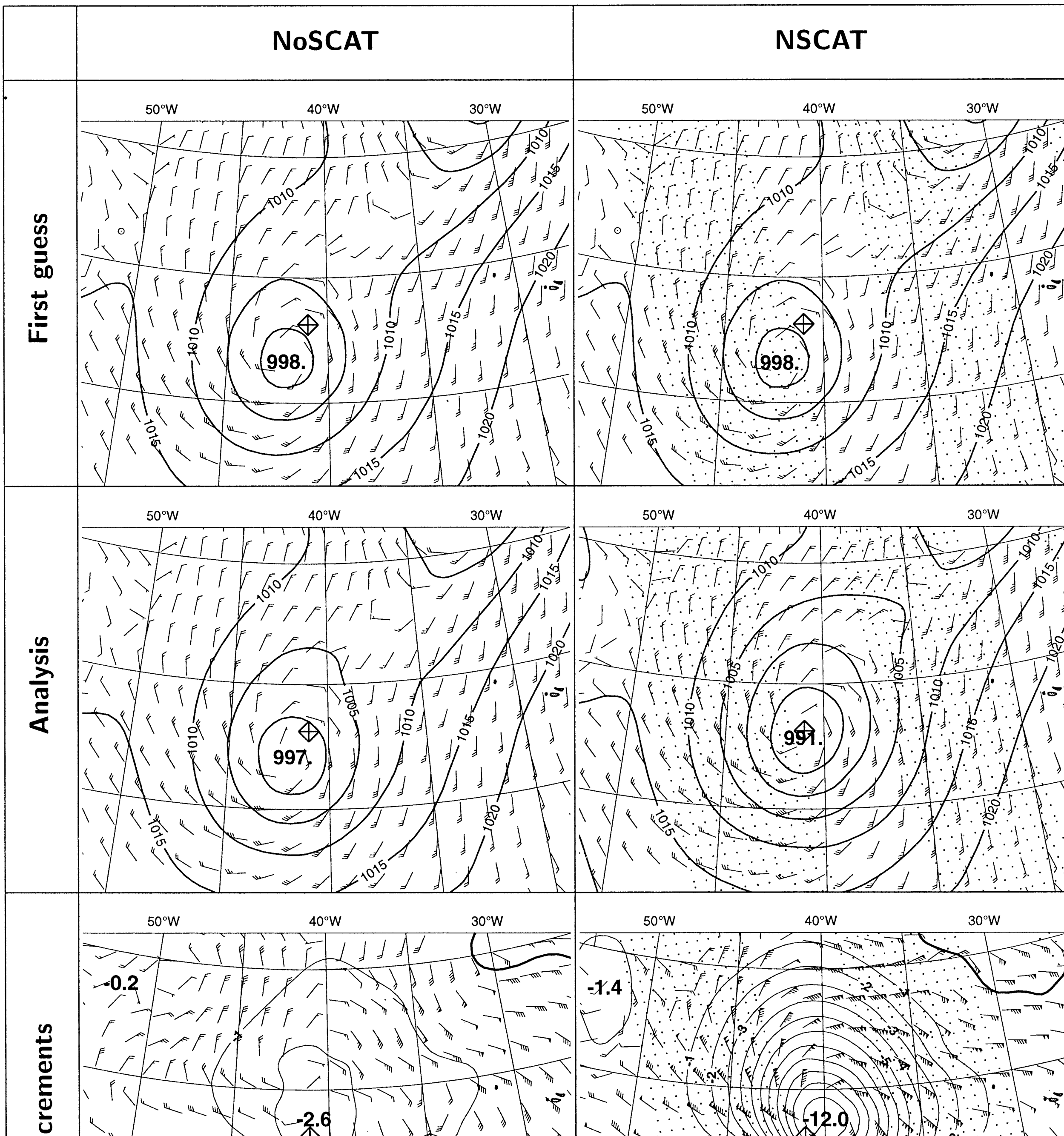

FIG. 17. Analysis impacts for Lili at 0000 UTC 26 Oct 1996 for 10-m wind (kt) and sea level pressure (5-hPa contour interval) from (left) NoSCAT and (right) NSCAT experiments, showing the (top) first guess, (middle) analysis, and (bottom) increments. For the analysis increments, wind speeds are multiplied by 10 and the sea level pressure contour interval is 1 hPa. The observed central pressure and position from the National Hurricane Center at 0000 UTC 26 Oct was 975 hPa at 38.1°N, 41.0°W.

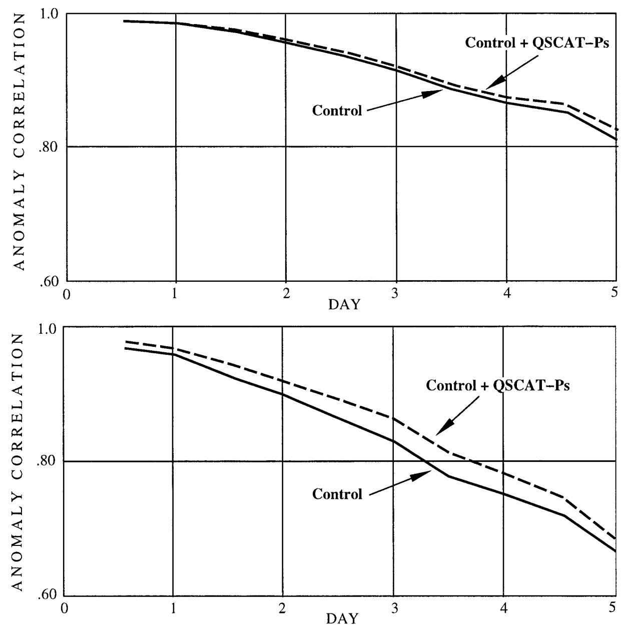

FIG. 18. Relative impact of QuikSCAT data on GEOS-3 model forecasts. The 500-hPa geopotental height anomaly correlations, averaged over four forecasts, are shown for the (top) Northern Hemisphere extratropics and (bottom) Southern Hemisphere extratropics.

resolution. For use in the ECMWF DAS, QuikSCAT winds are retrieved at 50-km resolution from the σ^0 values in the NESDIS near-real-time data products. The winds are assimilated with the same two-ambiguity cost function used for *ERS-1* and NSCAT. As with NSCAT the two ambiguities must be separated in direction by at least 135°, and a sea ice check is performed. Also the outermost portions of the swath are not used. Additional quality control procedures are planned (e.g., Figa and Stoffelen 2000).

The early ECMWF QuikSCAT experiments have shown only small positive and negative impacts on global scores of forecast skill, but impacts on particular storms and other regional-scale meteorological features are occasionally very positive. Experiments to date have focused on the European storms of December 1999. Two very powerful, small-scale cyclones hit the north of France around Christmas Day 1999. Operational centers around the world largely missed the appearance of these storms in the 2–7-day forecast time range. (The UKMO is the one notable exception.) Consequently, there was little or no warning when these fast-moving, damaging storms reached the Brittany coast.

Figure 19 shows 6- and 7-day forecasts for Control and QuikSCAT experiments, respectively, as well as verifying analyses, for the first of these storms, the so-called Christmas Day storm. Less than 24 h before landfall, the storm was a small feature in the sea level pressure field in the central Atlantic near 46°N, 30°W (evident in the left middle panel as an upside-down Ω shape in the 1000-hPa contour). This feature is not present in the Control experiment 6-day forecast, but is evident in the QuikSCAT experiment, shifted toward the north and east. After the storm made landfall, there is clear evidence of a small-scale, high-amplitude storm crossing northern Europe in the QuikSCAT experiment (near 55°N, 10°E), but none in the Control experiment. The presence of this feature in the forecast, albeit somewhat displaced, would have alerted forecasters well in advance of one of the most damaging storms in France in the last century.

10. Use of scatterometer winds by marine forecasters

Scatterometer data provide the ability to correct weather analyses over the oceans and to improve forecasts and warnings of severe weather conditions for maritime interests. Peteherych et al. (1981) demonstrated the potential improvement in coastal marine forecasting due to SASS. Atlas et al. (1999) showed examples in which scatterometer wind patterns are able to represent the precise location, structure, and intensity of significant meteorological features. Scatterometer data therefore can have very substantial impacts on the surface wind analysis. For example in Fig. 20, with NSCAT data, the wind flow analysis for the North Atlantic shows a small cyclone. This feature was not at all indicated by the GEOS-1 analysis that does not include NSCAT observations, which shows only a broad cyclonic circulation. In general, when NSCAT identifies an otherwise undetected feature, it can be corroborated by independent observations or subsequent analyses. In the case shown in Fig. 20, the subsynoptic-scale cyclone is consistent with the patterns of SSM/I rain rates and cloud imagery (not shown). In addition, the NSCAT ambiguities show the cyclone clearly, and the cyclone appeared in the operational NCEP, ECMWF, and DAO analyses 12 h later.

National Weather Service forecasters at the Marine Prediction Center (MPC) in Camp Springs, Maryland, began to view NSCAT wind retrievals early during the short life of the ADEOS-1 spacecraft. The MPC is responsible for issuing wind warnings for mariners for the western North Atlantic and central and eastern North Pacific Oceans. Wind warnings for extratropical cyclones are categorized as "gale" for wind speeds of 17–23.5 m s^{-1} and as "storm" for wind speeds > 23.5 m s^{-1}. MPC forecasters as part of the forecast process analyze surface features and sea level pressure every 6 h for both the North Pacific and North Atlantic Oceans. These analyses are then transmitted directly to ships at sea via high-frequency radiofacsimile.

Prior to NSCAT, MPC forecasters ocean wind observations were limited to passive microwave wind speeds from SSM/I, scatterometer winds from the *ERS-1* and *ERS-2* spacescraft, and conventional ship and buoy observations. Each of these datasets has limitations. The low spatial resolution of conventional ship and buoy observations was discussed in section 2. SSM/I measurements are attenuated in areas of precipitation and liquid cloud thus limiting wind retrievals near fronts and cyclones. Also, SSM/I cannot differentiate between gale and storm force winds. The *ERS-1* and *ERS-2* scatterometers have a narrow swath width, often limiting wind retrievals to portions of cyclones.

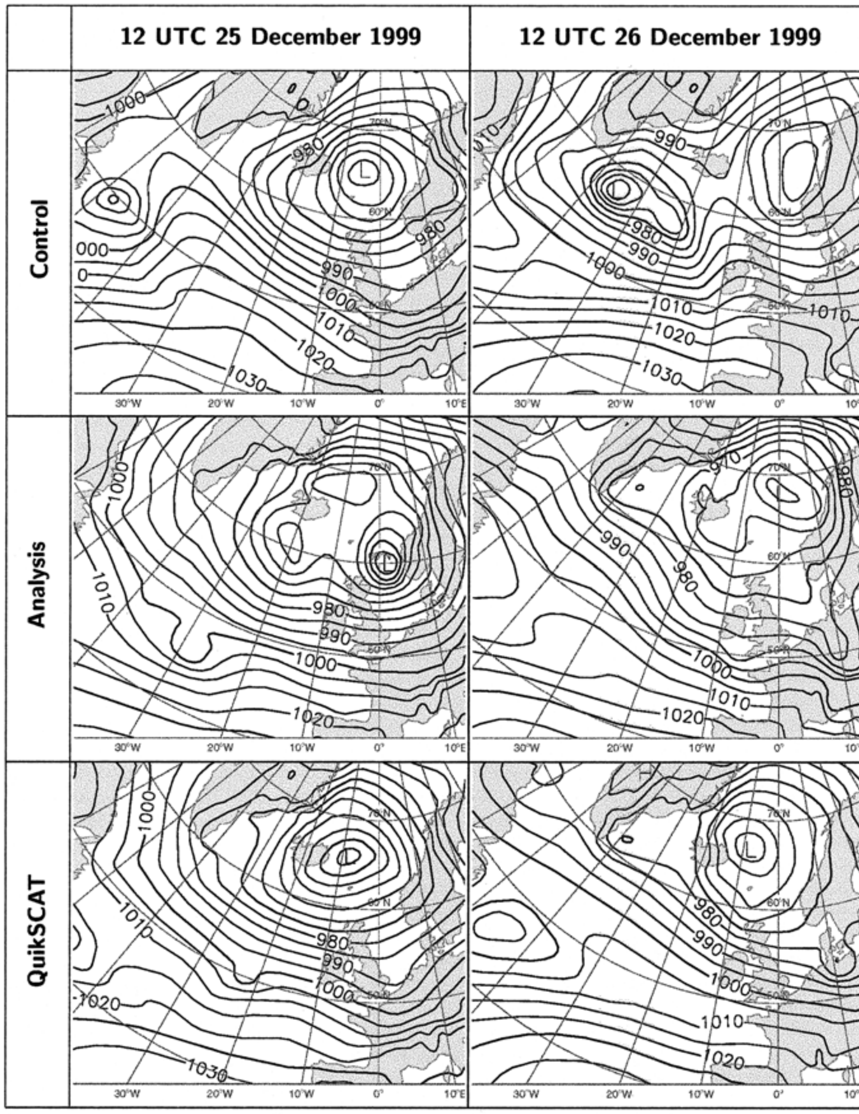

FIG. 19. The Christmas Day storm analyses and forecasts of sea level pressure (5-hPa contour interval) verifying (left) 1200 UTC 25 Dec 1999 and (right) 1200 UTC 26 Dec 1999, showing the (top) Control forecast, (middle) operational analysis, and (bottom) QuikSCAT forecast.

NSCAT, due to the larger swath widths, gave MPC marine forecasters excellent views of the detailed wind structure of extratropical cyclones. NSCAT winds rapidly became a tool used by all MPC forecasters. The less traveled (by ship), and thus less observed higher latitudes were no longer a data-void area. Forecasters could view individual cyclones frequently, usually every 12 h, or even more frequently at high latitudes where the scatterometer data swaths overlap. In particular, the evolution of occluded fronts in maturing ocean cyclones became evident as a major wind boundary. Consequently, forecasters adopted the Shapiro and Keyser (1990) cyclone model based on the evidence provided by NSCAT winds. During the analysis process, cyclone or anticyclone center locations and intensities, and frontal locations from the NCEP global model short-range forecasts, were often adjusted in location and intensity based on features depicted by NSCAT. Warnings were occasionally raised or lowered based on NSCAT winds. No longer were wind retrievals restricted to the gale warning category. Wind speeds well into the storm category were retrieved.

Another positive impact that resulted from using NSCAT winds was that MPC forecasters became more skilled at interpreting conventional satellite imagery.

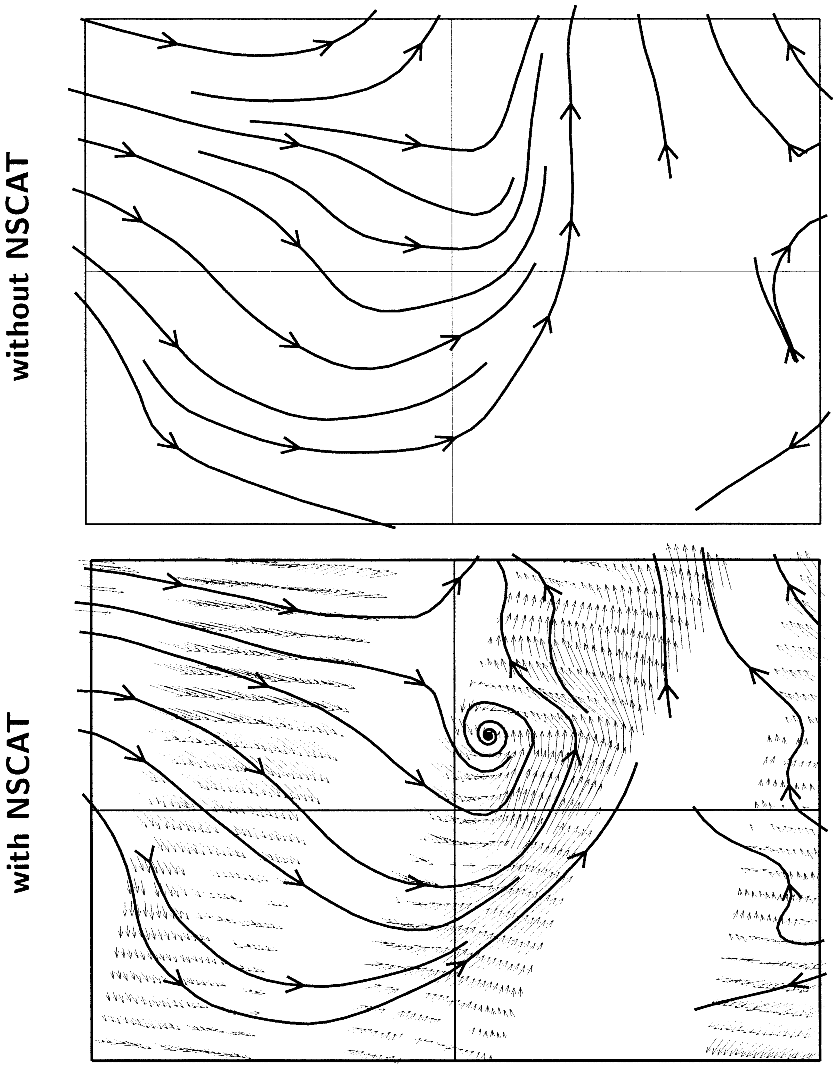

FIG. 20. The wind flow analysis for the North Atlantic (centered at 40°N, 25°W) (bottom) with and (top) without NSCAT data for 1200 UTC 15 Sep 1996. [After Atlas (1997b).]

In comparing conventional imagery (IR and visible) to the underlying NSCAT wind fields, subtle cloud features were no longer so subtle. Frontal placements were also less subjective.

The positive experience with NSCAT encouraged MPC forecasters to quickly adopt QuikSCAT data, which has been available within MPC since August 1999. In contrast to NSCAT, MPC forecasters have the ability to use QuikSCAT data as an underlay on their operational workstations while analyzing frontal positions and pressure centers. It is now not unusual for QuikSCAT data to be displayed on the computer monitors of all four MPC shift forecasters at any given time, and for these data to have a strong influence on the forecasts and warnings that are issued. Recently, QuikSCAT winds have been reported to identify tropical depressions prior to their detection by other observations (Katsaros et al. 2001; Sharp et al. 2001).

11. Conclusions

Scatterometer data over the oceans are able to delineate precise locations and structures of significant meteorological features, including cyclones, anticyclones, fronts, and cols. (The locations are precise to within the 25-km resolution of the retrieved winds.) As such, their use by marine forecasters can result in improved analyses, forecasts, and warnings for ships at sea and other marine interests. The use of scatterometer observations in data assimilation systems can extend their usefulness substantially and lead to improved sea level pressure analyses, improved upper air analyses of both wind and geopotential, and improved short- and extended-range numerical weather forecasts. Typically, forecast improvements are skewed toward the Southern Hemisphere extratropics, with the length of a useful forecast extended by as much as 24 h in some DASs. In the Northern Hemisphere extratropics forecast improvements are episodic: overall the Northern Hemisphere extratropics impact is close to neutral or slightly positive, but occasionally the depiction of an individual storm is improved substantially, leading to a more skillful forecast.

Certain caveats apply to the above remarks because all impacts have a dependency on the DAS used to conduct the experiments. First there is the issue of data redundancy, that is, does the new data source provide new information to the DAS? Depending on the skill of the DAS and the number, type, and quality of data already being assimilated, the new data will be more or less redundant. When data are redundant in this way, we might say there is less room for improvement and expect that improvements will be smaller. Second, is the new data effectively utilized? Demonstrable analysis improvements can be rejected by the forecast model. Data rejection typically occurs when a single variable or level is improved without consistent balanced increments to other variables and levels. For scatterometer data we have seen that effective utilization requires that the assimilation properly treats the asynoptic nature of these data, correctly weights the data, accounts for the observational errors, and allows the data to influence other variables and levels. As DASs evolve, the effects of data redundancy and data rejection tend to be opposed. Improved DASs leave less room for improvements but may be more capable of effectively using the data.

In this paper we have reviewed both simulated and real data impact experiments (OSSEs and OSEs, respectively). These two types of experiments are intertwined, with real data experiments often suggesting follow-on simulation experiments and vice versa. We have seen that if OSSEs are designed and evaluated carefully, then the OSSE results provide useful predictions of the corresponding real data OSE results. Because OSSEs provide a clean experimental setup, they help in the design of DAS improvements, allowing controlled testing of new procedures and tuning of existing ones. In this way OSSEs refine DAS procedures for new data sources in advance of the actual availability of the data, thereby preparing weather forecast centers to more rapidly use the new data. Furthermore, the ability of OSSEs to predict OSE results suggests that OSSEs are an effective tool to evaluate proposed observing systems. However, OSSE results are also system dependent, and cannot be extrapolated to current or future DASs with radically different characteristics.

We conclude with some comments about SeaWinds on QuikSCAT, a new scatterometer of a fundamentally different design, which was launched in June 1999. Engineering studies of SeaWinds before launch indicated that these data will have characteristics different in important ways from NSCAT. Notably SeaWinds offers better coverage than NSCAT, with no nadir gap. This by itself suggests further positive impacts beyond those of NSCAT. However, the quality of the SeaWinds and NSCAT data differ. First, the reliability of SeaWinds directional information varies across the swath. We already observed this in the preliminary SeaWinds data. Second, rain contamination seems to have a more detrimental effect on SeaWinds than on NSCAT. We anticipate that the utilization of SeaWinds data will evolve from the NSCAT baseline. In particular, more sophisticated ambiguity removal and quality control procedures may be required. And so, scatterometry research and the quest to make the best use of scatterometer data for weather analyses and forecasting continues with SeaWinds.

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APPENDIX: List of acronyms

ADEOS	Advanced Earth Observing System (Japan)
AES	Atmospheric Environment Service (Canada)
ALIAS	Control experiment plus ambiguous JPL wind vectors
AMI	Active microwave instrument
ASCAT	Advanced scatterometer
CONV	Experiment using conventional data only
CTW	Cloud track wind
DAO	Data Assimilation Office
DAS	Data assimiliation system
DMSP	Defense Meteorological Satellite Program
ECMWF	European Centre for Medium-Range Weather Forecasts
ERS	European Remote Sensing Satellite
ESA	European Space Agency
GEOS	Goddard Earth Observing System
GLA	Goddard Laboratory for Atmospheres
GSFC	Goddard Space Flight Center
IR	Infrared
JPL	Jet Propulsion Laboratory
KNMI	Royal Netherlands Meteorological Institute
METOP	Meteorological Operational satellite
MPC	Marine Prediction Center

NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NCEP95	NCEP DAS operational in 1995
NESDIS	National Environmental Satellite, Data, and Information Service (NOAA)
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Analysis and Prediction System
NRCS	Normalized radar cross section
NSCAT	NASA Scatterometer
NSCAT-N	NSCAT nudged wind
NSCAT-S	NSCAT wind speed
NWP	Numerical weather prediction
NoSCAT	experiment without scatterometer data
OSE	Observing system experiment
OSSE	Observing system simulation experiment
QEII	Queen Elizabeth II
QuikSCAT	NASA Quick Scatterometer
Rms	Root-mean square
SASS	Seasat-A Satellite Scatterometer
SATEM	Satellite temperature sounding
SMMR	Scanning multichannel microwave radiometer
SPEED	Control experiment plus JPL wind speeds
SSM/I	Special Sensor Microwave/Imager
TAO	Tropical Atmosphere Ocean
TIROS	Television Infrared Observation Satellite
TOVS	TIROS Operational Vertical Sounder
T62	Sixty-two wave truncation in NCEP95
UKMO	U.K. Met Office
UTC	Coordinated universal time
VAR	Control experiment plus winds chosen by a 2DVAR analysis
VTPR	Vertical Temperature Profile Radiometer
3DVAR	Three-dimensional variational data assimilation scheme

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